I. Technical Final Report

This project (U.S. Department of Energy Grant No. DE-FG02-97ER54387) was originally awarded to Dr. Rex Gandy (PI) of Auburn University for the 3 year period from Nov. 1, 1998 through Oct. 31, 2001. This project is a collaborative effort involving Auburn University, the University of Texas, and MIT. The technical goal is to measure electron temperature fluctuations using electron cyclotron emission (ECE) on the Alcator-C tokamak. The physics goal is to understand the role that these fluctuations play in plasma transport, in particular the influence of electron temperature fluctuations on anomalous transport.

During the past year(Dec 1, 1998 through Nov. 30, 1999(a great deal has been accomplished on this project. The main contribution of the Auburn researchers was the design and implementation of the radiation collection system[1]. This radiation collection system is now installed on C-Mod and is working well. The University of Texas has designed the radiometer part of the system and that is also functional. Preliminary data has been attained and the physics part of the research program is commencing.

During the course of this project, Dr. Rex Gandy was offered and accepted a position with the Physics Department at the University of Idaho. This position begins on Jan. 1, 2000. Auburn University has agreed to allow this grant to be moved to the University of Idaho. The present grant with Auburn will be terminated. The involvement of Dr. Christopher Watts of the Physics Department at Auburn University will continue through a sub-contract from the University of Idaho to Auburn University. This document represents a formal request to allow the completion of this project at the University of Idaho.

I.1 Introduction

Although tremendous progress has been made in recent years in magnetic fusion research, the basic physics of transport is still not well understood. In general, magnetic fusion devices still observe a level of transport that far exceeds the levels predicted from neo-classical theory, so called anomalous transport. Some turbulence based theories have been proposed[2], but plasma fluctuation measurements are still insufficiently advanced to

make detailed comparisons with the competing theories. Therefore one of the main goals of fusion research should be to measure plasma fluctuations with as much detail and resolution as possible. It is only with a firm grounding in experimental investigation that an understanding of anomalous transport will emerge.

For the past few years a team of scientists from Auburn University, the University of Texas, and MIT have made progress in the measurement of plasma electron temperature fluctuations on Alcator C-Mod. An experimental ECE system based on the successful approach employed on TEXT and TEXT –U has been designed, built and implemented on C-Mod. The ECE systems used on the Texas tokamaks led to many new physics results [refs 2-8}. These experiments will not be described in detail, but a brief overview will be presented to illustrate the breadth of physics issues which can be investigated on C-Mod.

The most important result of the TEXT ECE research was the first measurement of broadband electron temperature fluctuations on a tokamak[3]. A fluctuation level of $\tilde{T}(t)/\bar{T} = 0.5\%$ was observed at mid-radius. This result ruled out the possibility that long-wavelength turbulence is responsible for the observed level of transport. The Auburn/Texas research team for the first time measured the correlation of the electron temperature fluctuation level with the sawtooth phase [4]. The amplitude of the temperature fluctuation level was observed to depend critically on sawtooth phase with a large peak in fluctuation level occurring at the sawtooth crash. Other work demonstrated that the turbulence has a significant poloidal angle dependence. In particular, the temperature fluctuation amplitude is peaked on the out-board side of the tokamak[5]. This result strongly suggests a ballooning-mode type source for the electron temperature fluctuations.

By performing electron temperature fluctuation measurements on Alcator C-Mod, one will be able to measure the change in core electron temperature fluctuation level with and without H-mode, an important experiment that was not available on TEXT. Also the higher magnetic fields available on C-Mod will allow for higher spatial resolution in the measurements.

In summary, I a joint scientific collaboration between University of Idaho, Auburn University , University of Texas, and MIT fusion researchers to measure electron temperature fluctuations on Alcator C-Mod has been successful during the last year. These measurements will make fundamental contributions to the understanding of electron energy transport in fusion devices.

I.2 Electron Temperature Fluctuation Measurements

I.2.1 ECE Background

When emitted by an optically thick plasma in thermal equilibrium and detected by a suitable radiometer, the electron cyclotron emission power is proportional to the plasma electron temperature at the EC resonance layer, but only to within a random error which depends on the radiation statistics. This error, here referred to as "wave noise" (alternatively thermal noise or Johnson noise), is small with respect to other systematic errors and ignored in most applications of ECE. However, an exception must be made when attempting to measure electron temperature fluctuations induced by high frequency turbulence in tokamaks because of the considerable spectral width and limited amplitude of the turbulent fluctuations[6].

The amplitude of the thermal noise fluctuations, which in these experiments accounts for virtually all of the signal noise, can be expressed in terms of the radiometer RF bandwidth, $\Delta \nu_C$, and the sampled video bandwidth of the turbulent phenomenon $\Delta \nu_{turb}$ [7]:

$$\frac{\delta P_{rms}}{\overline{P}} = \sqrt{\frac{2 \Delta \nu_{turb}}{\Delta \nu_C}} \qquad (1)$$

where P is the output signal of the single-mode radiometer, proportional to the detected power input and δP_{rms} is the amplitude (root mean square) of the fluctuations of P. In the TEXT-U experiment we observed the above high frequency ECE signal fluctuations as seen in previous experiments[8,9]. The experimentally determined amplitude of these fluctuations in the band from 25 to 225 kHz is very near (± 5%) to the value one obtains from expression (1) using the measured IF filter bandwidth: $\delta P_{rms} / P = 6.3\%$.

I.2.2 Technique Description

Because the ECE thermal noise completely obscures the measured coherent high frequency temperature fluctuations, the actual time history of the T_e fluctuations is not accessible. However, we can still measure the *average* amplitude of these fluctuations through correlation analysis of two suitably chosen ECE signals whose turbulent temperature fluctuations are correlated while the thermal radiation fluctuations are uncorrelated[10]. In the absence of systematic errors the measured cross-correlation of the two signals will yield the correlated signal power.

A radiometer channel output produces a signal proportional to the instantaneous collected power, $S(t)=(\bar{T}+\tilde{T}(t))\,(1+\tilde{N}(t))$, where $\bar{T}$ and $\tilde{T}(t)$ are the average plasma temperature and its fluctuating component, respectively, and $\tilde{N}(t)$ is the radiation wave noise. The observed (zero time-delay) cross-correlation, $R_{12}=\overline{\tilde{S}_1\tilde{S}_2}$, where $\tilde{S}$ is the measured signal minus the mean $\bar{S}$, between two radiometer channels identifies the common normalized electron temperature fluctuations,

$$\frac{\tilde{T}_{e,rms}}{\bar{T}_e}=\sqrt{\frac{R_{12}}{\bar{S}_1\bar{S}_2}}\,. \qquad (2)$$

The method does not require that the radiometers be absolutely calibrated. However, it does require an appropriately long integration time to reduce the statistical error to well below the coherent temperature fluctuation amplitude, particularly if one is seeking spectral information through suitable analysis. To this end, the limit of statistically meaningful information ("noise level"), ε, can be determined for R_{12} by:

$$\varepsilon(R_{12})=\frac{\sigma_1\sigma_2}{\sqrt{N}} \qquad (3)$$

where σ is the standard deviation in S and N is the number of independent samples. This limit has been well verified both by numerical simulations of random data and bench tests using a calibrated noise source.

The CRECE (correlation radiometry of ECE) method implemented on Alcator C-Mod correlates the signals from two disjoint RF bands which, because of the cyclotron frequency gradient in a toroidal magnetic field and the finite width of the emission layer, overlap in space. Because wave noise arises from the beating of waves only within the selected frequency band, the wave noise in the two separate bands is uncorrelated.

However, the overlapping sample volumes ensure that the temperature fluctuations (with wavelengths the order of or greater than the emission volume size) will be common to both signals.

I.2.3 Experimental Apparatus

A multi-channel heterodyne radiometer tuned to the 2^{nd} harmonic X-mode electron cyclotron frequency is used. The view is along the tokamak major radius in the equatorial plane. The signal will be downshifted by a heterodyne radiometer to a frequency range between 2 and 18 GHz with a local oscillator frequency near 280GHz (second harmonic at 5T magnetic field).

The Alcator C-Mod radiometer optics has been designed to maximize poloidal spatial resolution. Poloidal resolution is of paramount importance, since the turbulent spectrum is believed to consist of abundant short-wavelength components. The need for high spatial resolution necessitates a focusing element. A metallic mirror is employed. Using diffraction-limited optics one obtains a transverse resolution of approximately 6 mm for B=5T operation. The design and construction of the ECE viewing path has been completed . This task was carried out in collaboration with Alcator C-Mod and University of Texas personnel.

Measurement of $\tilde{T}_{e,rms}$ is obtained from cross-correlation between pairs of ECE signals selected using narrow band IF filters in a multi-channel system. A sketch of the system is shown in figure 1. The signal from the radiometer is separated into 4 equal-width frequency bands by a multiplexer covering the 2 to 18 GHz range. These signals are amplified with broadband (2-18GHz) intermediate frequency (IF) amplifiers with a nominal gain of 32 dB. The amplified signal is selected by the IF filters and then detected using square-law diode detectors. These crystal detectors convert the RF power into proportional dc voltages in the 10 MHz to 18 GHz range. Chebychev bandpass filters a with typical selectivity of 6dB/octave per stage will be used. Previous experiments with tunable filters have verified the transition from complete correlation, in the case of overlapping frequency intervals, to nearly absent correlation (<0.5%) for separations greater than ~1.5 times the filter bandwidth.

Schematic of Signal Detection

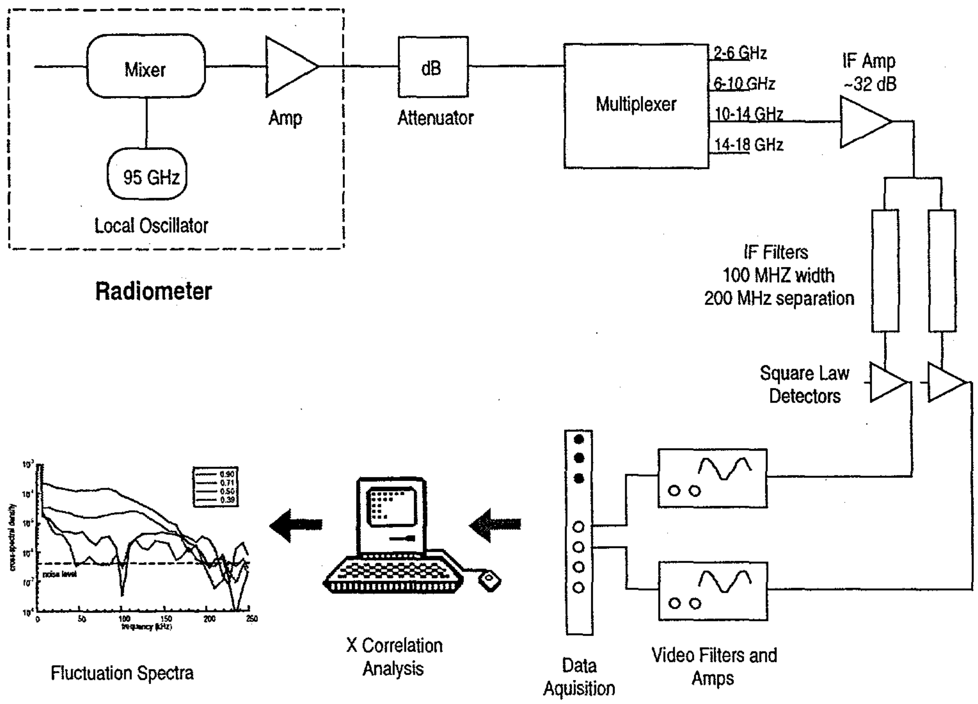

Figure 1. Schematic of the ECE system for measurement of electron temperature fluctuations.

A typical IF filter bandwidth will be 300 MHz. For Alcator C-Mod magnetic field gradients this corresponds to a distance of ~1 mm in the cold electron cyclotron resonance position along the major radius. This separation is considerably less than the emission layer thickness, which is on the order of 5 mm[11] .

The location of the resonance layer in the plasma is determined by the magnetic field in conjunction with the frequency of the detected radiation. A scan of the minor radius will be accomplished by varying the magnetic field slightly from 5T. For radial correlation studies we will use single fixed filters in conjunction with tunable YIG filters.

Output from the crystal detectors will be routed to a set of video amplifiers which provide lowpass filtering in addition to a gain of 20 dB to the signal. Measured core turbulence in TEXT-U suggests that no extra information is gained by increasing the video bandwidth above 250 kHz. We will therefore digitize the signal at 500 kHz.

I.3 Future Work

TEXT-U proved to be an excellent test bed for the diagnostic concept of correlation radiometry of ECE (CRECE) for measurement of core temperature fluctuations. As a medium size tokamak, it combined the advantages of reasonable size with a high discharge repetition rate, allowing ease in diagnostic development. The methodology of core temperature fluctuation measurement has now been proven on a medium size tokamak, and the scope of the experiment needs to be expanded to more relevant regimes of fusion plasma physics.

The obvious next step is to study temperature fluctuations on a larger machine, such as Alcator C-Mod. C-Mod is an excellent machine to study these fluctuations primarily because of the availability of H-mode discharge conditions. Experiments comparing fluctuations during H and L-mode phases are vital to understanding anomalous transport and C-Mod will be able to provide this plasma environment.

Alcator C-mod also offers certain other advantages. One of these is the opportunity to measure temperature fluctuations on a high density, high magnetic field machine. Aside from the obvious need to establish scaling laws in different plasma regimes, the high field/high density combination means C-mod plasmas are optically thick over most of the plasma minor radius. This allows measurements of the temperature fluctuations up to the very edge of the plasma without the worry of contamination of density fluctuations due to small optical depth. Further, the increased magnetic field (relative to the major radius) means the inherent wave noise of the ECE signals is reduced (albeit only slightly), allowing better statistics and measurement of smaller fluctuation levels. An additional area of emphasis will be to look at edge temperature fluctuations. Due to the high optical depth of the Alcator C-Mod plasma the region of optically thick emission (where electron temperature can reliably be deduced) extends very close to the plasma edge. We are planning to install separate radiometer systems to investigate these areas.

Another planned experiment will involve a slight augmentation of toroidal focussing mirror mount. By connecting a linear feedthrough to a moveable hinged pivot, we can rotate one of the toroidal focussing mirrors so that the two views overlap at some radial range. This allows for dual interferometric correlation techniques in addition to the single line of sight techniques being used. This allows for time sensitive temperature fluctuation measurements to be made. This modification will also allow toroidal correlation of ECE signals to be measured.

The experiment would involve using both overmoded waveguides and a single radiometer. At a given frequency (radial position) the resonance positions would go from complete overlap through partial overlap to separate resonance volumes. This experiment would be done on a shot to shot basis with angle changed remotely while C-Mod is in recool mode. All radiometer frequencies can be mapped out in this experiment. There is a possibility of Doppler shifted emission clouding the experiments since one of the views moves away from perpendicularity to the toroidal field.

VI. REFERENCES

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